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COMPUTATIONAL ANALYSIS OF 1 kW PEMFC STACK: IV CHARACTERIZATION AND OPTIMIZATION

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Abstract

This computational study focuses on the IV characterization (current-voltage-power) of a 1 kW-24 Vdc proton exchange membrane fuel cell (PEMFC) stack. Leveraging an online MATLAB package, we simulated the performance of a 42-cell stack, incorporating air and hydrogen flow rates. The simulation parameters included a stack efficiency of 46%, an air flow rate of 2400 lpm, and an operating temperature of 55 °C. Our objective was to comprehensively investigate the IV characteristics of the PEMFC over a 1-hour duration. The results demonstrate a linear relationship between current and voltage, with a maximum power output of 2 W and a voltage range of 0 to 45.5 V. The study contributes valuable insights into PEMFC dynamics, offering a computational approach for characterizing and optimizing performance. This work lays the foundation for further exploration of PEMFC behavior under varying conditions, paving the way for advancements in fuel cell technology.

Keywords: PEMFC, IV Characterization, Computational Simulation, Stack Efficiency

1 Introduction

Fuel cells have emerged as a promising technology for clean and efficient energy conversion, offering a viable alternative to traditional combustion-based power generation. Among various types of fuel cells, PEMFCs have garnered significant attention due to their high energy efficiency, low environmental impact, and versatile applications. As researchers and engineers strive to enhance the performance and viability of PEMFCs, computational analysis has become an indispensable tool in understanding the intricate dynamics of these systems. This article delves into the computational analysis of a 1 kW PEMFC stack, focusing on the crucial aspect of current-voltage (IV) characterization and subsequent optimization. The IV curve is a fundamental performance metric for PEMFCs, providing insights into the electrochemical processes within the cell and influencing the overall efficiency of the power generation system. By employing advanced simulation techniques and optimization algorithms, researchers aim to unravel the complexities associated with PEMFCs and tailor their operational parameters for optimal performance.

The research on the computational analysis of a 1 kW PEMFC stack with a focus on IV characterization and optimization is imperative for several compelling reasons. These reasons underscore the necessity of such investigations to advance the field of fuel cell technology and contribute to the broader goals of sustainable energy production: PEMFCs are known for their high efficiency in converting chemical energy into electrical energy. However, achieving and maintaining optimal efficiency levels is a complex task. This research aims to uncover opportunities for efficiency enhancement through detailed computational analysis, ultimately contributing to more effective and sustainable energy conversion processes. A comprehensive understanding of the IV characteristics is fundamental to deciphering the performance of PEMFCs. Computational analysis allows researchers to delve into the intricate electrochemical processes occurring within the fuel cell stack, providing insights into factors influencing performance. This knowledge is crucial for identifying bottlenecks, optimizing operating conditions, and improving overall system efficiency.

As PEMFC technology evolves, there is a need for continuous improvement in design to meet the increasing demands for energy efficiency and reliability. Computational analysis facilitates the exploration of various design

parameters, enabling researchers to optimize the geometry, materials, and operational conditions of the fuel cell stack. This optimization process is vital for achieving higher power density and longer operational lifetimes. The commercial viability of PEMFC technology is closely tied to the overall cost of production and operation. Computational analysis allows researchers to explore cost-effective design modifications and operational strategies without the need for extensive physical prototypes. Identifying cost-efficient solutions contributes to the economic feasibility of PEMFC technology, making it more competitive in the energy market. PEMFCs are recognized for their potential to provide clean energy with minimal environmental impact. Understanding the performance characteristics and optimizing PEMFC stacks can further enhance their environmental benefits by ensuring efficient energy conversion and reducing resource consumption. This aligns with the global imperative to transition towards cleaner and more sustainable energy sources.

2 Literature Review

The current era marks a pivotal moment for hydrogen, serving as a new energy vector that holds the potential to enhance global energy independence and facilitate decarbonization across various economic sectors. Electrolysis of water, involving the breakdown of H_2O into oxygen and hydrogen gas through an electric current, is a key method to produce hydrogen sustainably. Utilizing a water electrolyzer and a fuel cell enables a seamless transition between electricity and hydrogen without on-site pollutant emissions. Amid prioritized objectives like reliability and lifespan, predicting the future applications of fuel cells remains challenging. Numerous studies have addressed this, focusing on fuel cell technology. This paper presents a model of a PEMFC using Matlab/Simulink, offering insights into the impact of different parameters on PEMFC efficiency and electricity production [1].

Fuel cells are a promising renewable energy source with the potential to offer secure, sustainable, and cost-effective energy solutions, contributing to economic, social, and environmental progress. PEMFCs utilizing polymers as electrolytes, have gained prominence due to their efficiency and versatility in various applications. The advantages of FCs include efficiency, cleanliness, economic, social, and environmental benefits, security, cost-effectiveness, and sustainable power generation. Despite their benefits, challenges such as high costs and maintenance requirements persist.

PEMFCs, among various types of fuel cells like phosphoric acid, molten carbonate, and solid oxide, stand out for their low operating temperature, fast start-up times, relatively lower component costs, high efficiency, and minimal environmental impact. Accurate modeling of PEMFCs is crucial for analysis and optimization, contributing to the development of more efficient, reliable, and environmentally friendly versions of the technology. Optimization algorithms play a critical role in determining PEMFC parameters, such as design, materials, operating temperature, and production rate, enhancing efficiency and cost-effectiveness [2].

Recent studies highlight the significance of perovskite proton conductivity, recommending Y-doped $BaZrO_3$ perovskite for electrochemical hydrogen FCs to improve efficiency [3]. Progress in barium zirconate proton conductors has also been reviewed, detailing current investigations to enhance hydrogen devices [4]. Optimizing PEMFC design variables involves traditional and metaheuristic optimization techniques. While traditional methods seek a single optimal solution, metaheuristic techniques, based on probabilistic methods, quickly find near-optimal solutions. Traditional techniques face challenges like slow convergence and difficulty handling complex nonlinear problems. Consequently, research papers increasingly focus on metaheuristic optimization algorithms for PEMFC parameter estimation due to their efficiency in addressing these challenges [2].

In 2011, the European Commission published the "Flight Path 2050" and set ambitious environmental goals for aviation. According to these goals, a 75% reduction in CO_2, a 90% reduction in NO_X, and a 60% reduction in noise emissions are targeted until 2050, specifically referring to typical aircraft manufactured in the year 2000. Given the increasing air travel demands, achieving these goals solely through evolutionary improvements of existing aviation technology appears challenging. It is widely acknowledged that hydrogen fuel cell systems can offer substantial improvements in civil aircraft design, including reduced noise, lower emissions, and enhanced fuel economy. This makes fuel cell-powered aircraft more aligned with the environmental objectives outlined in the "Flight Path 2050". To strengthen competencies in the aviation sector, weight reduction and reliability improvement of these fuel cell system designs are deemed crucial. The cooling subsystem within an aviation fuel cell system is identified as a critical component, accounting for up to 50% of the total system weight [4]. Efficient heat rejection is emphasized as vital for aviation fuel cell systems,

particularly as fuel cells in aviation move towards higher power outputs in the megawatt range for commercial airliners [5]. Existing studies have explored various cooling approaches, including using the aircraft surface for heat transfer, Outer Mold Line cooling, and innovative hydrogen cooling concepts. System reliability is paramount in aviation, often achieved through redundancy. Current standards require a minimum redundancy of 2.25 for fuel cell-powered airliners, but this increases the total system weight and limits payload capacity. To address this, a shift towards system simplicity is proposed, reducing the number of components and thereby improving reliability, reducing weight, and increasing the power-to-weight ratio [6].

3 Methods and materials

Computational Framework: This study leveraged a computational approach using an online MATLAB package to simulate the IV characteristics of a 1 kW-24Vdc PEMFC stack. MATLAB provides a versatile and powerful platform for numerical simulations, facilitating the modeling and analysis of complex systems like fuel cells.

PEMFC Stack Design: The simulation focused on a PEMFC stack with a power output of 1 kW and an operating voltage of 24Vdc. The stack consisted of 42 individual cells arranged in series, each operating under similar conditions. The nominal stack efficiency was set at 46%, reflecting the conversion efficiency of electrical power from hydrogen and air input.

Operating Conditions: The simulation considered operational parameters relevant to practical PEMFC systems. The air and hydrogen flow rates were integral components, with an air flow rate set at 2400 liters per minute (lpm). The simulation was conducted at an operating temperature of 55°C, representing a common operational range for PEMFCs.

Simulation Duration: The simulation spanned a duration of 1 hour, providing a comprehensive analysis of the IV characteristics over an extended period. This duration allowed for the observation of transient behavior, stability, and performance variations within the fuel cell stack.

Computational Execution: The online MATLAB basic package utilized for the simulation incorporated relevant algorithms and models for PEMFCs. The computation involved solving the governing equations of the fuel cell, considering factors such as electrochemical reactions, mass transport, and

thermal effects. The simulation was executed iteratively to capture the dynamic response of the PEMFC stack under varying load conditions.

Data Collection and Analysis: Data on current, voltage, and power characteristics were collected throughout the 1-hour simulation. Various performance metrics, such as power density, voltage efficiency, and current density, were computed to evaluate the overall performance of the PEMFC stack under the specified conditions. This computational study employed an online MATLAB package to simulate the IV characteristics of a 1 kW-24Vdc PEMFC stack. The design and operational parameters were carefully chosen to reflect real-world conditions, and the simulation methodology allowed for a detailed investigation of the fuel cell's performance over a 1-hour duration.

4 Simulation block Diagram

The simulation of a fuel cell system with a particular emphasis on the output generation based on specified constants (1), and input variables represent in leftside of stock cell. The simulation employs a model is treating as either a 1-D array or a matrix, depending on the configuration, shown in figure 1. The maximum value of the output is determined by the minimum or maximum of the input, with operators applied across the input vector in the case of multiple inputs. The simulation incorporates a general expression block, utilizing u as the input variable name for both air and fuel. This study provides a comprehensive understanding of the dynamics and behavior of the fuel cell system through a flexible and adaptable simulation framework, offering insights into the impact of specified constants and input variations on the system's performance.

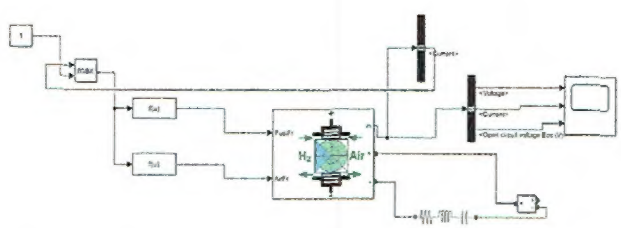

Figure 1: Block diagram and flow chart for simulation of fuel cell

5 Results and Discussion

The simulation focused on the transient response of a proton exchange membrane fuel cell (PEMFC) under constant fuel supply conditions, providing valuable insights into the dynamic behavior of the system. Figure 2 depicts the nature of current and voltage with time for a consistent supply of fuel and oxygen or air.

5.1 Voltage Fluctuation

The voltage fluctuation in the proton exchange membrane fuel cell (PEMFC) system exhibits distinct temporal patterns. Initially, between 0 to 750 seconds, the voltage fluctuation is comparatively lower, suggesting a relatively stable system during this period. However, from 750 seconds to 2750 seconds, there is a noticeable increase in voltage fluctuation, indicating a phase of heightened system dynamics. Beyond 2750 seconds, the voltage fluctuation decreases, emphasizing the system's ability to return to a more stable state. The voltage range of 44.5V to 45.5V throughout the experiment underscores the dynamic nature of the PEMFC system, potentially influenced by factors such as fuel supply variations and system response time.

5.2 Current Fluctuation

The current in the PEMFC system exhibits significant fluctuations over time, and these variations provide valuable insights into the system's dynamic behavior. Between 250 seconds and 600 seconds, the current fluctuation is observed to be lower, suggesting a period of relative stability. However, after 600 seconds, the current fluctuation increases and peaks at 1500 seconds, indicating a phase of heightened system dynamics. The sustained high fluctuation continues until 2750 seconds, after which the current fluctuation decreases, suggesting a return to a more stable state. The observed current range from 10^{-2} to $5x10^{-2}$ A signifies the dynamic response of the PEMFC system to changes in fuel supply and operational conditions.

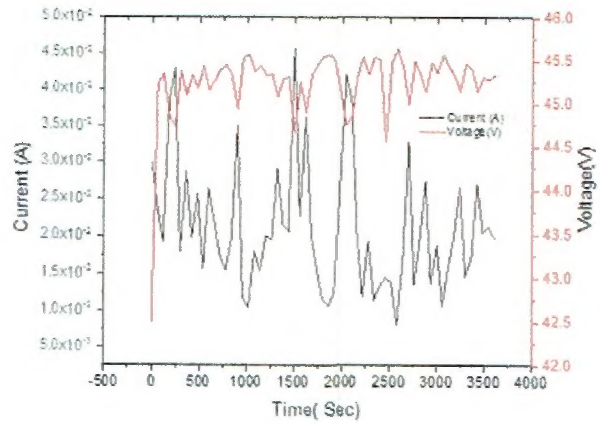

Figure 2: Fuel supply time vs Current and Voltage

Comparisons with previous studies, notably [7] Smith et al., reveal similarities in the fluctuation patterns of current and voltage. Despite differences in the voltage range and fluctuations, the shared characteristics indicate consistent behavior in PEMFC systems under certain conditions. This comparison highlights the reproducibility of certain dynamic phenomena in PEMFCs and provides additional context for interpreting the current study's results. It underscores the importance of understanding these fluctuations for designing and optimizing PEMFCs for practical applications. The dynamic performance and loading characteristics of the PEMFC system are crucial for evaluating its practical applicability. The study observes that successful loading occurs with a step current density of 1.5 Acm^{-2} after activation, emphasizing the importance of controlled activation processes. Issues such as membrane dehydration are identified as significant factors affecting dynamic performance. The study's findings align with the broader goal of achieving favorable responses to high step currents, facilitating rapid loading to high-power output. These insights contribute valuable guidance for designing and controlling the dynamic loading of PEMFCs [8], enhancing their reliability and efficiency in diverse applications.

5.3 Voltage and Power Characteristics

Figure 3 illustrates the voltage and power characteristics of the PEMFC stack at different current densities. The observed nature of voltage demonstrates a linear decrease with increasing current density, indicating a typical behavior within the tested operational range. Conversely, the power exhibits a linear

increase with current density. The recorded maximum power reaches 2 W, while the voltage reaches a maximum of 45.5 V. Notably, the intersection point of power and voltage occurs at 0.03 A, indicating a critical operational point where both parameters align.

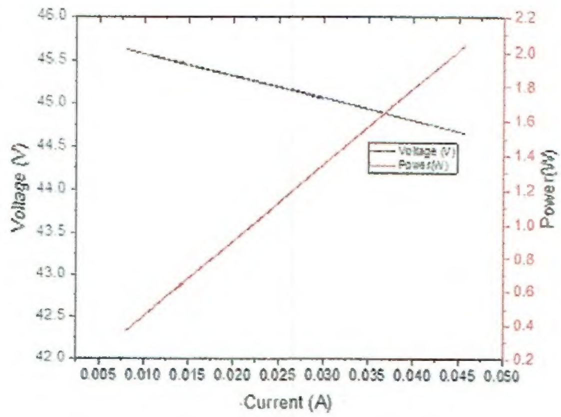

Figure 3: Current vs Voltage and Power

The voltage and power characteristics observed in this study align with the findings reported [9] Kuan et al., suggesting a consistent behavior across different experimental setups. This similarity provides corroborative evidence and reinforces the reproducibility of certain phenomena in PEMFCs. The linear relationship between voltage and current density, along with the intersection point, is a characteristic shared with the prior study, contributing to the broader understanding of PEMFC performance under varying conditions. To further evaluate the PEMFC stack, additional experiments were conducted using the Rigor fuel cell test system (RG24020) at 75 °C and 80% relative humidity. The polarization curve displayed a typical pattern, achieving an output power of 15.8 kW. The current experienced a decline from 270 A to 190 A at a stack voltage of 58.5 V, leading to a sharp drop in output power from 15.8 kW to 11.11 kW. These results closely resemble those reported by Xiong et al. [10], indicating a consistent trend in the impact of backpressure on PEMFC performance.

6 Conclusion

In conclusion, the investigation into the voltage and power characteristics of a homemade PEMFC stack reveals a linear decrease in voltage with increasing current density, while power exhibits a linear increase. The maximum recorded power and voltage reach 2 W and 45.5 V, respectively, with an interesting intersection point at 0.03 A. The congruence of these findings with the study by Kuan et al. [9] highlights the reproducibility of PEMFC behavior across different experimental setups. Additionally, the examination of backpressure effects on stack performance aligns with previous research, emphasizing the impact of pressure conditions on current, voltage, and power outputs. These insights contribute to a comprehensive understanding of PEMFC dynamics, guiding further research and practical applications. The observed trends underscore the importance of optimizing operational parameters for enhanced PEMFC performance in various environmental conditions.

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